James Webb Space Telescope (JWST) Stationkeeping Monte Carlo Simulations

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24 Mar 2014

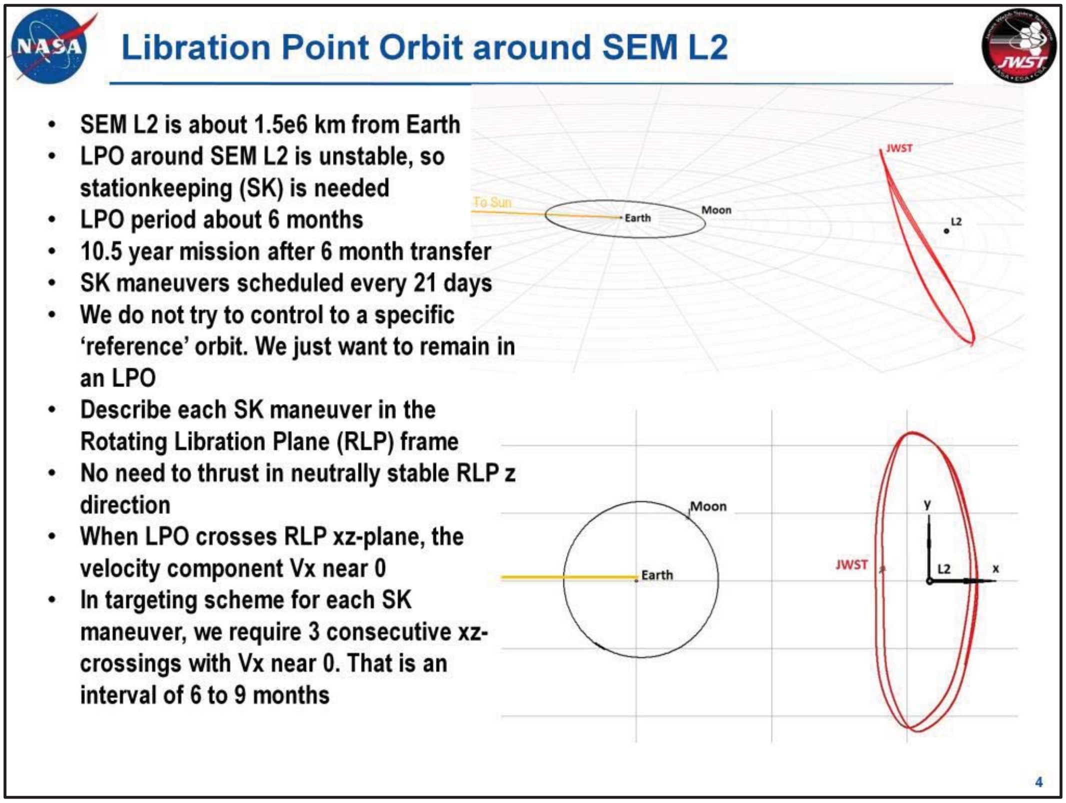
24th International Symposium on Space Flight Dynamics
Laurel MD

Introduction: The Challenges

- JWST will fly in a libration point orbit (LPO) around the Sun-Earth/Moon (SEM) L2 point, so regular Stationkeeping (SK) maneuvers will be required
- JWST is a large, complex spacecraft that will make large attitude changes, resulting in significant changes (~35%) in Solar Radiation Pressure (SRP)
- The observation schedule is ‘event-driven’, so it will not be possible to precisely predict the attitude and the SRP long-term
- JWST is restricted in the SK thrust direction. In particular, it cannot thrust in the Sunward direction
- The above features present challenges to the planning of each SK maneuver, where we must estimate accelerations six to nine months into the future

Introduction: Our Approach

- This presentation describes the SK maneuver planning process for JWST
- First describe the heritage 'End-of-Box' method used to produce a conservative but realistic SK budget for JWST
- Next describe enhancements for Monte Carlo simulation made in 2013
- Summarize the Monte Carlo results
- Finally discuss future work to be done to address changes in observation plans

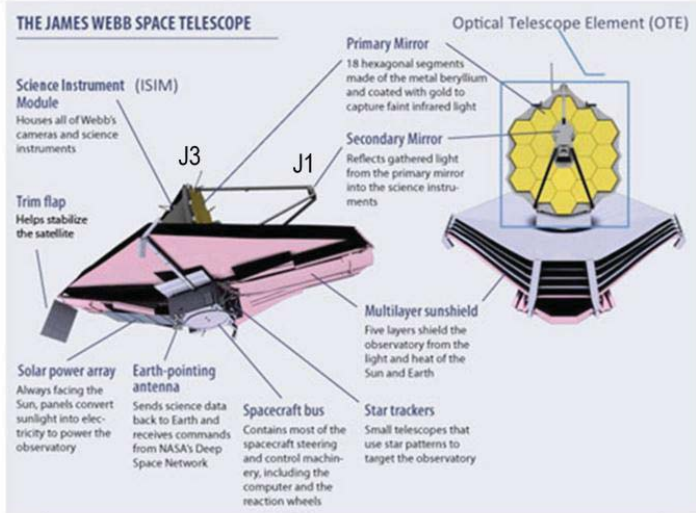


The actual JWST orbit may look different, depending on launch date.
However the shape of an LPO in the xy plane remains about the same. Only the size changes significantly.

The last bullet requires some explanation. For each SK maneuver we define a targeting (differential correction) problem where we fix the thrust direction and solve for the thrust magnitude so that, at the next x-z crossing, Vx = 0. After that problem converges we modify the targeting problem so that Vx = 0 at the 2nd x-z crossing.
(In general, at the 1st x-z crossing Vx is close to 0 but no longer 0.) Finally after the 2nd problem converges we target the maneuver so that Vx = 0 at the 3rd x-z crossing. To be more precise, we only require that Vx be near 0, which is sufficient to maintain a LPO.

JWST Spacecraft

- Built primarily by Northrop Grumman Aerospace Systems (NGAS) and NASA Goddard
- Infrared (IR) telescope, so must be shaded from Sun
- Large Sunshield, size of a tennis court
- 5 layers to reflect Sun's radiation and keep the IR instrument cold
- Telescope is fixed in body frame
    - Entire spacecraft must repoint to repoint the telescope
- Spacecraft can repoint over a range of 50 deg in pitch, so the Solar Radiation Pressure (SRP) on the Sunshield can vary widely
    - Minimum SRP is 35% less than maximum



JWST Constraints

- To keep the observatory protected from Sunlight, JWST is limited in its pointing range
  - Sun pitch angle between 0 and -53 deg during SK
    - +5 to -45 deg during science operations
  - Sun roll angle between +5 and -5 deg
- This constraint limits range of SK SCAT thruster angles
  - Rotation Libration Point (RLP) Quadrant 1 (“Q1”): Between 37.1 to 90.1 deg from RLP x axis
  - RLP Quadrant 4 (“Q4”): from -37.1 to -90.1 deg from x axis
    - Analysis has shown that -90.1 deg is the optimal direction in this range, so simulation only considers that direction in Quadrant 4
  - In particular, cannot thrust along –x direction

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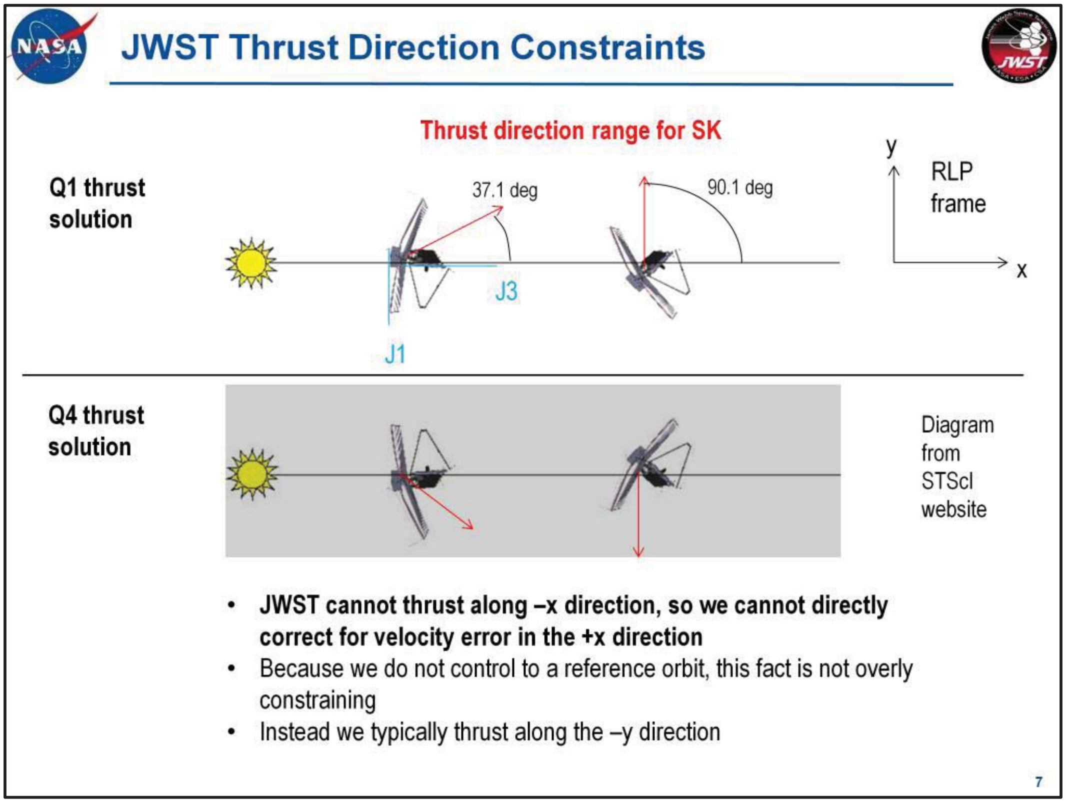
These limits are illustrated on the next slides.

For more details on how these limits are based on the spacecraft configuration, see the backup charts titled
JWST Bus and Thrusters
and
JWST Pointing Constraints, Thrust Constraints



These images convey the range of attitudes during SK, but the angles are not precisely correct for SK.
The spacecraft attitude in these pictures is actually for the science phase, where the Sun pitch range is
+5 deg to -45 deg.
In the SK phase we allow Sun pitch 0 to -53 deg.

Momentum Unloads and Maneuver Schedules

- As JWST changes orientation the reaction wheels must absorb angular momentum
- Occasionally it will be necessary to use thrusters to perform Momentum Unloads (MUs) for angular momentum change (delta H)
  - There are as many as 8 MUs in 21 days between SK maneuvers
- If Center of Mass (CoM) is not at its nominal location, along thrust direction, then an MU is not a pure couple and delta-H produces delta-V
- Northrop Grumman Aerospace Systems (NGAS) has generated 27 possible torque tables, labelled 111 to 333, based on CoM location uncertainty
  - For heritage End-of-Box analysis, torque table 222 was identified as producing the largest SK budget. It also produces the largest average MU magnitude
- Space Telescope Science Institute (STScI) provided 190 representative observation schedules, each about 14 months (420 days) long, with an associated schedule of SK maneuvers and MU maneuvers

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For the presentation I will skim over this information, or cut it down for the sake of time.
The main point to convey is that the CoM location may be off-nominal, so that each MU will induce a delta-V.
NGAS modeled 27 possible CoM locations, and we used them all in the Monte Carlo simulation.
The exact schedule of MU delta-V's depends on the observation schedule and the torque table.

Observation Schedule is Event-Driven

- During operations, STScI will produce a planned observation schedule for the next 7 days
- However the actual observation schedule is "event-driven"
  - A "target of opportunity" (e.g. a supernova) may arise. STScI can change the observation in 2 days to include the new observation
  - If the Fine Guidance Sensor cannot lock onto a guide star for a target, then the observation will be skipped
- Consequently when planning SK maneuvers, we may not know the attitude even 7 days into the future
  - Hence we cannot know future SRP precisely, and we must be prepared for a range of possible SRP accelerations

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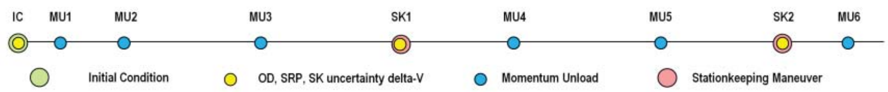
This is the key feature of the JWST mission that makes SK budget a challenge to predict. We will not know in advance what attitude JWST will fly, so we cannot predict the SRP accurately.
We also cannot predict MU maneuvers.

Stationkeeping Planning Model

Source: 2010 MCDR Orbital Analysis

- **Start with an initial state in Sun-Earth L2 Libration Point Orbit**
- **Apply orbit perturbations**
  - SRP force perturbation, due to error in attitude and coefficient of reflectivity C_R
  - OD velocity error (dynamics insensitive to OD position error)
- **Insert Momentum Unload (MU) maneuver for observation schedule provided by STScI**
  - May be as many as 100 MU maneuvers in ~420 day schedule
- **Insert SK maneuver each 21 days**
  - Plan SK maneuver without knowing future attitudes: assume nominal SRP force, no MU maneuvers
  - Plan SK maneuver with targeter, requiring three xz-plane crossings with Vx near 0
  - Find the optimal thrust angle from the allowed range
- **Apply orbit perturbations immediately after SK maneuver**
  - SRP force pert, due to error in attitude and coefficient of reflectivity C_R
  - OD velocity error (dynamics insensitive to OD position error)
  - Maneuver execution error
- **Repeat until end of ~420 day observation schedule**
  - Solve for 19 SK maneuvers



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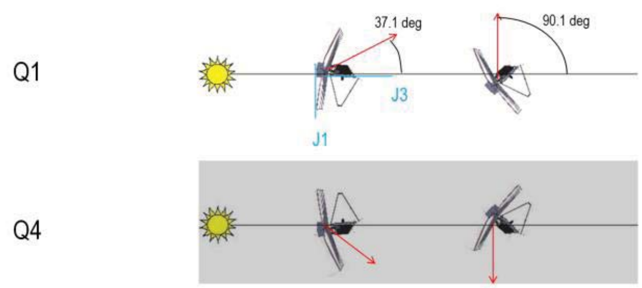
Heritage "End-of-Box" Model

- **End-of-Box model was developed by Mark Beckman and Leigh Janes in 2006**
- **The code has since been maintained and updated by Cassie Alberding**
- **End-of-Box approach assumes that orbit perturbations are stressing cases**
- **First apply –x errors, and solve for optimal Q1 maneuver**
- **Then change to +x errors, and solve for optimal Q4 maneuver**
- **To estimate required SK delta-V, average the Q1 and Q4 delta-V's, assuming that the two are equally likely to occur**
- **Analysis showed that JWST needed SK budget of 25.5 m/s for 10.5 years, or 2.43 m/sec per year**
  - **Typical Sun-Earth LPO mission needs about 1 m/sec per year**



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I am skipping details about modeling assumption. They are in the paper.

Modeling Changes from End-of-Box

- Attitude modeling
- More accurate SRP modeling
- Improved OD solution
  - See JWST OD paper by Sungpil Yoon in this conference
- Monte Carlo simulation
- Distributed computing

SRP Attitude Modeling

- **Between SK maneuvers we used one of two approaches to model "truth" attitude for JWST**
  - **STScI provided 190 representative observation schedules. We have the option in the Monte Carlo simulation of randomly draw an STScI schedule for each trial**
  - **We also created 100 randomly generated (RG) schedules**
    - **Sun pitch and Sun roll is drawn from a uniform distribution of allowed values**
    - **Attitude changes at regular intervals of 6 hours, similar to STScI schedule**
  - **The RG schedules represent a more stressing case, to have greater confidence that the SK budget is sufficient to support the full mission.**

- **During SK maneuver planning, we do not know future attitude. Instead with use "cannonball" SRP model and assume a fixed, nominal SRP area**
- **After experimentation, we found that a nominal SRP area value of 140 m^2 (60% of the way from minimum to maximum value) works well for both the STScI observatory schedules and the RG schedules.**

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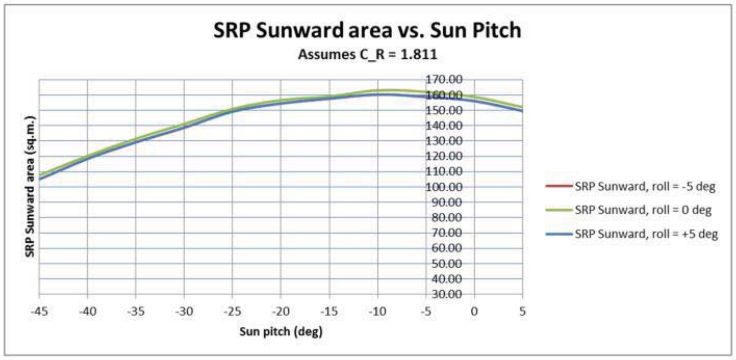
The key point here as that we model attitude, and so SRP, different ways for different phases.

Leading up to an SK maneuver, we will know the observation schedule accurately so we can model the SRP accurately.
For SK budget planning we consider a collection of representative collection of observation schedules, and make random draws for the Monte Carlo simulation.

Planning an SK maneuver, we will not know the future observation schedule, so we plan to model SRP with cannonball model and a nominal area.
The SRP nominal area we use is in the middle of the SRP range.

SRP Force Modeling

- The SRP for JWST shows strong dependence on attitude, and JWST can alter its attitude significantly during the mission. Therefore it is important to use an attitude-dependent SRP model for SK.
- We used a JWST spacecraft model provided by NGAS as input to NASA Goddard's Solar Pressure and Atmospheric Drag (SPAD) tool, which uses ray-tracing to accurately compute SRP, taking into account self-shadowing.
- We then adapted an "N-plate" SRP plug-in provided by Analytical Graphics Inc. (AGI) to interpolate the SPAD data table, and compute SRP for STK/Astrogator.
  - The same SRP plug-in works in Orbit Determination Tool Kit (ODTK), which is important to maintain consistency between SK and OD modeling. (See JWST OD paper by S. Yoon.)



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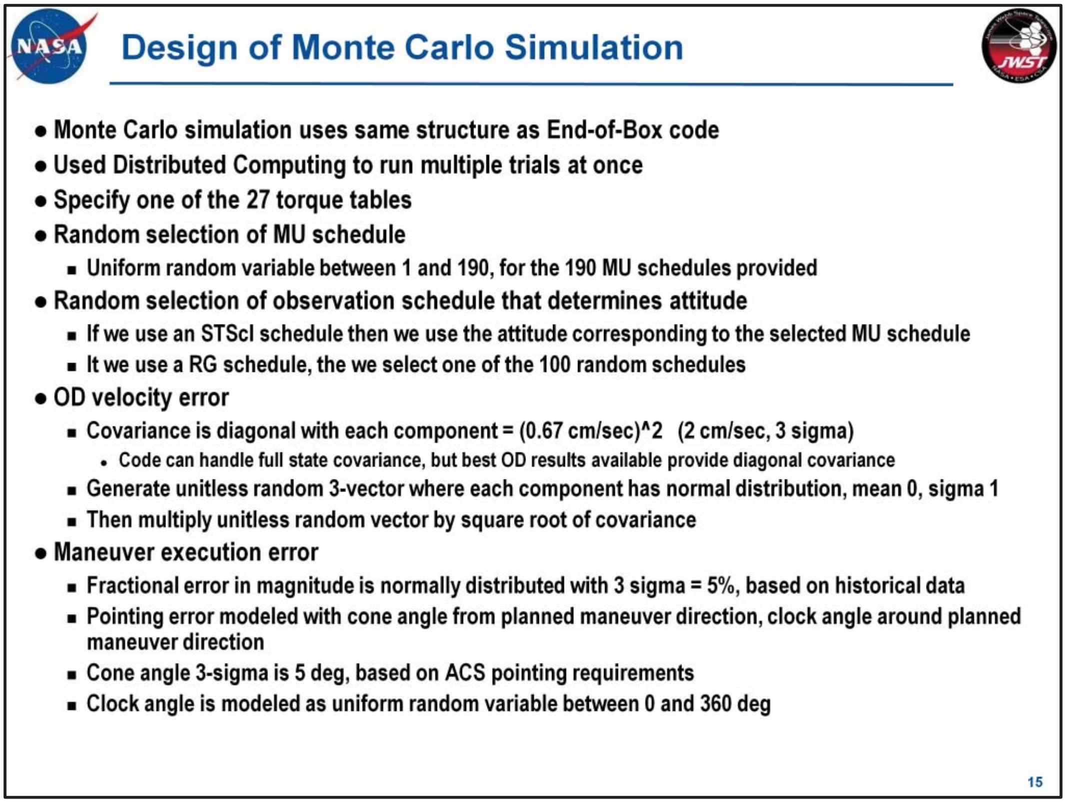
The SRP plug-in we use, based on SPAD computations, is an essential part of the modeling process.
I want to emphasize that the high-accuracy SPAD computations are performed offline. For the plug-in we simply interpolate an SRP table generated by SPAD.



To keep the presentation brief, I will emphasize that the Monte Carlo simulation is structured very much the same was as the End-of-Box simulation.

The key differences in the Monte Carlo are shown in chart “Modeling Changes from End-of-Box”:
We randomly draw errors (vs. fixed worst-case errors in End-of-Box)
We randomly draw obs schedule that determine attitude
We model SRP much more accurately with an attitude-dependent plug-in to STK & ODTK
We model much larger variation in SRP than in End-of-Box (though other errors are smaller than in End-of-Box)

We look at all torque tables (vs. End-of-Box that focused on one torque table 222)
We use Distributed Computing to run 6 trials simultaneously, and explore more possibilities
We use the OD error requirement of 2 cm/sec (3-sigma).
(Previous End-of-Box simulation used 2.53 cm/sec. Sungpil Yoon has shown in companion paper that we can do better than 2 cm/sec, 3-sigma. We used the requirement value to be conservative.)

Monte Carlo Results: Largest Delta-V's

- OD error 2.0 cm/sec (3 sigma)
- Truth attitude drawn from 100 RG schedules
- SRP nominal value 140 m^2
- Modeling Uncertainty Factor (MUF) 1.10
- SK budget for 10.5-year mission

Torque table	SK mean (m/sec)	SK sigma (m/sec)	99th percentile (m/sec)	99th percentile with MUF (m/sec)	Number of trials completed
111	20.56	0.69	22.62	24.88	1082
112	19.84	0.67	21.83	24.01	153
113	20.03	0.72	21.19	23.31	332

- OD error 2.0 cm/sec (3 sigma)
- Truth attitude drawn from 190 STScI schedules
- SRP nominal value 140 m^2

Torque table	SK mean (m/sec)	SK sigma (m/sec)	99th percentile (m/sec)	99th percentile with MUF (m/sec)	Number of trials completed
111	17.21	0.89	19.90	21.89	132

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For torque table 111, with the largest delta-V, we ran over 100 trials to get a reliable budget value.
In other cases shown we ran over 100 trials.
For each of the torque tables we ran at least 24 trials to get a sense of which torque tables were "worst", then we focused simulation effort on the worst cases.

There is not sufficient time in a 15-minute presentation to explore all the parameters in this simulation.
One aspect is the effect of torque table (so MU maneuvers) on SK budget, in combination with the assumed SRP nominal value.
Note that torque table 111 models the CoM at the desired location, so there are no MU delta-V's.
For the End-of-Box, torque table 222 was used, which produces the largest MU delta-V's
Why do we get the largest delta-V when there are no MU maneuvers?
In the Monte Carlo we model much larger variation in SRP, and we speculate that MU delta-V can actually help maintain the LPO in that situation.
There is evidence to support this hypothesis.
In cases where we assumed a nominal SRP value closer to the average, then torque tables with more MU maneuvers produced the largest SK delta-V.

Monte Carlo Results: Further Studies

- In all we performed more than 8500 Monte Carlo trials
- We modeled every torque table for
    - OD error 2.0 cm/sec (3 sigma)
    - SRP nominal value 140 m^2
    - STScI and RG observation schedules
- We demonstrated that we could skip SK maneuvers that would be < 12 cm/sec, and maintain the LPO
- For a subset of most stressing torque table, we modeled OD error 1.67 cm/sec (3 sigma) to assess the effect of reducing OD error
- For OD error 2.0 cm/sec (3 sigma) and for STScI and RG observation schedules, we varied the SRP nominal value. We demonstrated that, *if* we can predict SRP more accurately, then we can reduce the SK budget.
    - If in flight operations we can improve SRP estimate by 3 m^2, then we can reduce SK budget by 2.6 m/sec: ~1 year of SK budget

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This slide is mainly to convey that we ran thousands of trials and performed various parametric studies using the new automated system.

It also shows that we are motivated to predict SRP as accurately as possible, to reduce the SK delta-V.

Conclusions and Future Work

- JWST is a large, complex spacecraft, with wide variation in attitude and SRP
- Range of SK thrust directions is limited. We cannot thrust in the Sunward direction, but we can cope with that constraint using a sub-optimal thrust direction
- Because the observation schedule is event-driven we cannot know the future attitude or SRP precisely
- The SK maneuver planning first used an End-of-Box approach to obtain a conservative but realistic SK budget of 25.5 m/sec for a 10.5 year mission
- We have adapted the End-of-Box SK simulation to create a Monte Carlo simulation
- The Monte Carlo simulation and Distributed Computing allows us to model errors more realistically and to try out more options
- Results of Monte Carlo, including Modeling Uncertainty Factor of 1.1, yield a SK delta-V of 24.88 m/sec for 10.5 years, within the established budget

- Perform SK budget analysis for updated observation plan from STScI
  - Average observation will be only 40 to 50 minutes vs. previous average between 5 and 6 hours
  - Plan to make observations of "moving targets" within our solar systems may require control closer to a reference orbit
- Investigate other SK algorithms to improve performance and address new constraints

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